An Innovative Approach for Controlling Fluid Power Systems Using Extended Reality

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Abstract.

This article showcases the application of Mixed Reality (MR) technology for communicating and controlling a fluid power system. The proposed system uses a combination of virtual and physical elements to provide users with an interactive and immersive experience with the HoloLens 2, a head-mounted device that overlays digital information onto the real-world environment allowing them to control components in real-time through a computational model developed through the Unity game engine. Visual Studio 2022 and Windows 11 SDK are the other tools implemented to generate a digital twin that can be used to manipulate a pneumatic excavator. In this system, the user can receive immediate feedback from the actions performed by the system while displaying process variables (e.g., pressure, flow, and acceleration). In addition, the project includes a physical component in the form of a hydraulic cylinder, which serves as the output of the mixed reality control system. This system requires establishing a bilateral connection between the HoloLens 2 and the microcontroller, for example, the ESP232 boardbase. Therefore, the electronic hardware will communicate wirelessly using a Wi-Fi network connection (API).

Additionally, the proposed interface is designed to be intuitive, easy to use, and versatile, allowing for a wide range of fluid power system applications (e.g., manufacturing, mobile, industrial, and robotics). The project demonstrates the potential of mixed reality technology for enhancing how humans interact with machines and equipment in the real world. The inherent traditional risks of using hydraulic technology will be mitigated.

Keywords. Mixed Reality, IoT, Fluid Power Systems, HoloLens 2.

NOMENCLATURE

API	Application Programming Interface
AR	Augmented Reality
MR	Mixed Reality

VR	Virtual Reality
VA	Virtual Annotations
SDK	Software Development Kit
HDM	Head Mounted Device
MRTK	Mixed Reality Tool Kit
PWM	Pulse Width Modulation
P_{out}	Output pressure after pressure regulator
P_{in}	Input pressure before pressure regulator
K_1	Pneumatic resistance of orifice 1
K_2	Pneumatic resistance of orifice 2
C	Compressibility of the system
q_1	Inlet flow in pressure regulator
q_2	Outlet flow from pressure regulator
F	External cylinder force
k	Spring constant
x	Piston displacement
v	Piston velocity
A	Area of piston bore

1. INTRODUCTION

When speaking of fluid power, one prominent example comes to mind: Excavators. A heavy-duty machine that exemplifies quite well the systems and principles characteristic of this field. They can dig, carry, and move heavy loads, benefiting from one principle, Pascal's law. In most hydraulic applications, the fluid medium is usually oil. However, some commercial machines leverage air power when the application involves grabbing or crushing light objects.

Hydraulic excavator have been studied and analyzed at length, whether if is for better efficiency, controllability or safety, studies in tele-operation have focused on remotely operating excavators, however, the use of Head Mounted Devices (HMD) for doing so is unheard off. The number of personnel qualified to operate fluid power equipment is decreasing more and more. Moreover, even when personnel is available to be trained, safety and cost are other drawbacks to overcome. To bridge the gap between lack of skilled workers and the increasing demand for these jobs, researchers [1],[2],**Error! Reference source not found.** have resorted to the use of Virtual Reality (VR) and other simulated experiences to train and upskill employees. In fact, the aviation industry has successfully used this approach to train pilots for decades [4].

Interaction with a fluid power system comes with certain risks and costs. For example, the pressure handles in these systems are around 4,500 psi for a commercial one when working with oil. Even if the process fluid is air, the risk is not mitigated. Consequently, the risks associated with an excavator operation are a constant factor regardless of the fluid process. As for the required skills to operate heavy equipment, the user should account for time needed for training, this time amounts to increased cost of operation and reduced allocation of resources which decreases productivity. In addition, the location where the training is carried out is expected to ensure safety. These factors lead to an increment in cost and productivity, not to mention that traditional training is not engaging. The virtualization of the training is an appealing alternative to lower operation costs, develop new skills, and provide a safe learning environment. However, a common concern when proposing a virtual learning environment is the inclusion of hands-on experience. This kind of virtualization is supposed to secure a platform with hands-on experience and teleoperation. Although non-technology replaces the need to interact with physical objects, it is through interaction that users acquire new skills. In combination with teleoperation, users can grab new skills and develop them in a safe environment as often as required.

Some companies have adopted virtual training modalities with a long track record in fluid power applications. These virtual modules or packages are intended to be used in virtual environments, specifically head-mounted devices (HDM). For instance, Festo [5] has a training program where MR assists in assembling pneumatic circuits and more complex systems. This company also reinforces that computer-aided systems prevent users from life-threatening or hazardous situations (environment and machinery). Furthermore, CIRO VR, a package developed by Festo, provides an experience close to real-life situations by enabling real-time simulation.

Other companies, such as Bosch, are pioneers in developing Mixed Reality packages. They conduct maintenance programs remotely, such as those reported by Neges et al. [6]. As a result, workers can execute tasks without using physical manuals or devices to interfere with their job. The company claims that mixed reality reduces the cost of training, keeps trainees safe, and, more importantly, the experience combines the real world and the 3D representation of the fluid power system [7].

These cases only address one side of the problem; they provide a safe way to interact with machines to minimize inherent risk for operation. However, the teleoperation of components is missing: the capacity to operate the machine remotely from a distance away from the equipment. Teleoperation in a mixed reality environment integrates different fields, communication protocols, digital twins, and control. Some researchers have successfully implemented and documented various architectures for the remote operation of actuators and fluid-power systems reliably and safely using different AR methods. An example of work in this field is the work presented by Fu et al. [8]. They proposed an integrated digital twin approach to support optimal excavation trajectory generation. The proposed architecture included the simulation of machine motion in a virtual environment to verify the feasibility of the generated trajectory and prevent accidents caused by structural interference. The effectiveness of the proposed approach was demonstrated via field tests with a scaled UCS prototype. The results showed that the proposed digital twin-based trajectory generation procedure could generate the optimal excavation trajectory in real-time and achieve better performance than manual operation [8].

Teleoperation has become a popular way to enhance worker safety in hazardous construction workplaces. Lee et al. [9] identified and presented the challenges, tasks, and opportunities in teleoperating excavators through rigorous analysis of past studies. The outcomes provide insights into future directions for teleoperation in construction workplaces, emphasizing the need for human-centered research to develop seamless human-robot interaction. Despite the complex and uncertain nature of construction workplaces, there has been an increasing interest in automation [9]. Hong et al. [10] examined the effects of virtual annotations (VAs) on the teleoperation performance of an excavator in a virtual environment. They performed some tests with an experimental group finding that the use of VAs helped the users to have significantly fewer collisions under adverse visual conditions compared to the control group without VAs. Their research suggests that VAs can improve an operator's situational awareness. However, they acknowledged the observed adverse effects, such as increased collisions on the back of the equipment. They concluded that further research is necessary to understand the mechanisms of forming a visual base and assessing an operator's cognitive load.

Sekizuka et al. [11] developed a system to remotely control a hydraulic excavator using virtual reality to evaluate operator skills. The results are promising. They can tell if the excavator is operated by an expert or not. However, the setup consists of several pieces of hardware, such as: a laptop computer, a joystick, camera, and excavator. All these devices limited the operator's range of motion and the remote control's windows.

A Mixed Reality headset can overcome the above shortcomings. A camera, virtual buttons, and the laptop's compute power are embedded in one Head Mounted Device (HMD), HoloLens 2.

The present study aims to create a teleoperation model for controlling a scaled pneumatic excavator from a mixed-reality environment, to the best of the author's knowledge no other experimental work in literature has reported the remote operation of an excavator using a HDM, other teleoperation applications have relied on cabins and screens to replicate the movements of the excavator, however the use of MR technology allows the user to be immersed in a real environment (i.e. construction site) without the need to be onboard the machine. For this proof of concept, the HoloLens2 device is used to manipulate one of the actuators of a miniature model of an excavator. In addition, the ESP232-based board serves as a bridge to enable communication between the HMD and the excavator. Finally, a user interface is designed to track operational variables, such as inlet pressure and displacement of the actuator, in real time.

This article is divided into four major sections, the second section discusses in detail the materials needed to build a prototype fluid machine and the necessary mechanical and electronic components as well as the software needed to demonstrate control of the fluid power system. The third section presents the reader with the qualitative demonstration of the integration of a physical pneumatic system and the means to control such system trough a wireless connection using mixed reality. This third section also proposes a methodology for improving the control of the system. A subsection of part three is dedicated to describing and testing a simple proportional control architecture to move the actuators in the pneumatic arm. The fourth and final section of the paper provides concluding remarks from this research and ideas for the improvement of this project.

2. MATERIALS AND METHODS

The present study focuses on the remote operation of the actuators of the scale model pneumatic excavator shown in Figure 1. The excavator model is partially operated from a Mixed Reality (MR) environment (Figure 4). The full system has four degrees of freedom or operation modes: swing, boom, arm, and bucket [12]. The valves control the compressed air flow to the cylinders, which power the excavator's arms and bucket movement. Thus, it is possible to move the pneumatic excavator in four directions: Boom lift and drop, arm curl in and out, bucket curl in and out, and swing arm to rotate the whole machine just as a real excavator would.

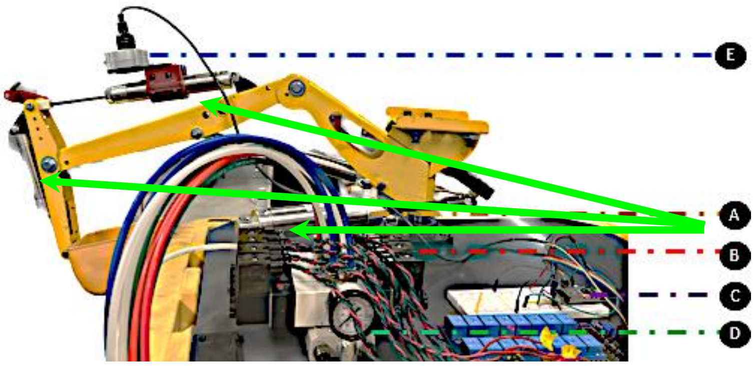

Figure 1 Pneumatic excavator model.

The model system comprises four pneumatic directional valves, four actuators, a Wi-Fi microcontroller module, and a pressure gauge. The position of each cylinder is set based on the differential pressure between its two chambers. The schematic diagram of the excavator shown in Figure 1 shows the various components of the machine and their connections (Table 1).

Table 1 Components and description of system elements

Part	Component	Reference	Qty	Description
A	Pneumatic actuators	A24040D	4	Double Acting with different diameters
B	Directional valves	AVS-523C1-120A	4	3-position 5-port (4-way) spool valve, center-closed
C	Wi-Fi microcontroller Module	ESP232	1	Provide Wi-Fi functionality.
D	Pressure gauge	G15-BD160-8LB	1	Monitor and control pressure [0-160 PSI]
E	String Potentiometer	SPD-4-3	1	Measure linear position using a flexible cable

A string potentiometer allows measuring the position of the piston as the cylinder extends; the string is attached to a stationary object mounted on the arm as shown in Figure 2. As the cylinder moves, it pulls the wire, which causes the spool to rotate and change the resistance value of the potentiometer. In addition, the string potentiometer is parallel to the cylinder's direction of movement, so when the cylinder moves, it causes the potentiometer's core to move along with it, changing its resistance value to track the position of the arm, a calibration process was conducted and shown later in Figure 5.

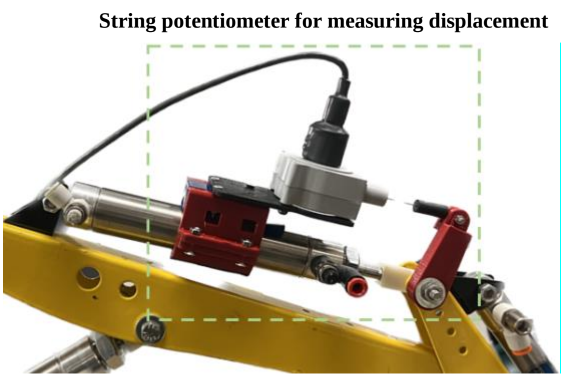

Figure 2 String potentiometer linear measurement.

To achieve this goal, a communication protocol via Wi-Fi is established between a microcontroller, ESP232 baseboard, and the HMD device, HoloLens 2, the configuration used for configuring this system is detailed in the next section.

2.1. System communication

The ESP232 Development Kit module bridges the Wi-Fi network and the relays on the electronics board to drive the valves. This development board includes a microcontroller, and a WIFI module, allowing it to connect to a WIFI network and communicate with other devices. An 8-relay module board is physically connected to the ESP232 module, where each solenoid is connected to a separate relay. When activated, the relay closes the circuit, enabling the voltage to pass to the solenoid to open or close the valves.

Virtual buttons created in the game engine Unity, are wirelessly connected to the ESP232 module to provide a user interface for controlling the valves and movement of the excavator. Each button is virtually connected to a separate pin on the ESP232, which is programmed to activate the corresponding relay and control the solenoid. With the levers for each solenoid, the user can quickly start the valves and control the movement of the excavator. Specifying the IP address and port number in the Unity code is essential to establish the connection to send commands to the ESP232 microcontroller module to operate the cylinders via the relay board.

2.2 *Electronics and control*

In addition to its mechanical components, the system shown in Figure 3 included a Wi-Fi module microcontroller, this device enabled the connection to a wireless network and, thus, two-way data transmission between a HoloLens 2 headset and the ESP232 microcontroller. Furthermore, the 8-relay module and the ESP232 Wi-Fi module, which are integral components of the system, have a shared operating voltage of 5V. This advantageous feature eliminates the need for additional hardware to couple the voltages, simplifying the wiring process and reducing the system's complexity. In addition, each relay serves the purpose of activating a corresponding solenoid controlling the corresponding valve's opening and closing, enabling reliable control of the flow through the system. It is worth noting that the pneumatic valves used in this excavator demonstrator model are not proportional, this fact makes the realization of precise displacement of the actuators nearly impossible.

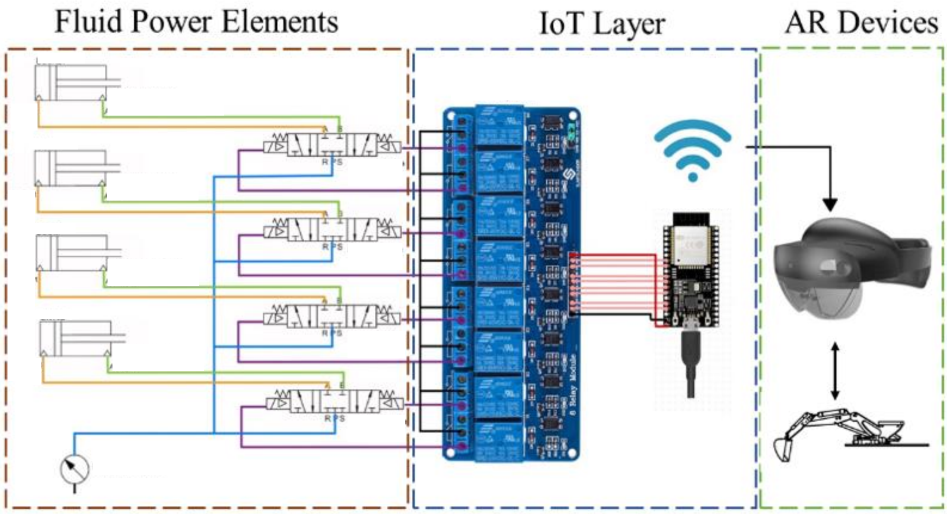

Figure 3 System architecture.

2.3 *Mixed Reality scene*

For this project, creating a visual interface that allowed the user to send and receive data from the hydraulic system was crucial. Therefore, a development tool such as Unity was an excellent choice for implementing a mixed-reality application. Unity is a game engine that allows developers to create virtual environments and immersive experiences for multiple platforms. Furthermore, Unity has a physics engine that enables user interaction with virtual objects, on top of easy integration of third-party tools such as Microsoft Mixed Reality Toolkit (MRTK), which receives user input solely using hand gestures from a HoloLens headset [6]. Hence, allowing users to manipulate digital content to control external physical machines, such as the excavator model in the present study. With this tool, the user can teleoperate the excavator and visualize an overlaid digital representation of the excavator position measurements, or others such as operating pressure or as in this study, the stroke of the main pneumatic actuator, the boom.

3. Results and Discussion

3.1. User Interface

The fluid power system was divided into four segments, each controlled by a pneumatic cylinder with three states: extended, retracted, and at rest. To control the different excavator parts, two buttons were assigned to each cylinder (arm, bucket, boom swing). Depending on the virtual button pressed by the operator, a unique coded variable was sent to the ESP232 baseboard microcontroller to execute the desired action (Figure 4). Additionally, a designated button was provided to clear all commands and set the pneumatic actuators at rest (all relays off). The displacement or position of the cylinder is displayed in real time on the HMD screen. The user can see the reading from the sensor in the excavator arm as time elapses. Similarly, the actuation of the solenoids to operate valves are all shown in the user interface as labeled in Figure 4. The buttons are color coded and numbered to imply extension (state 1, red) or retraction of the cylinders (state 2, blue).

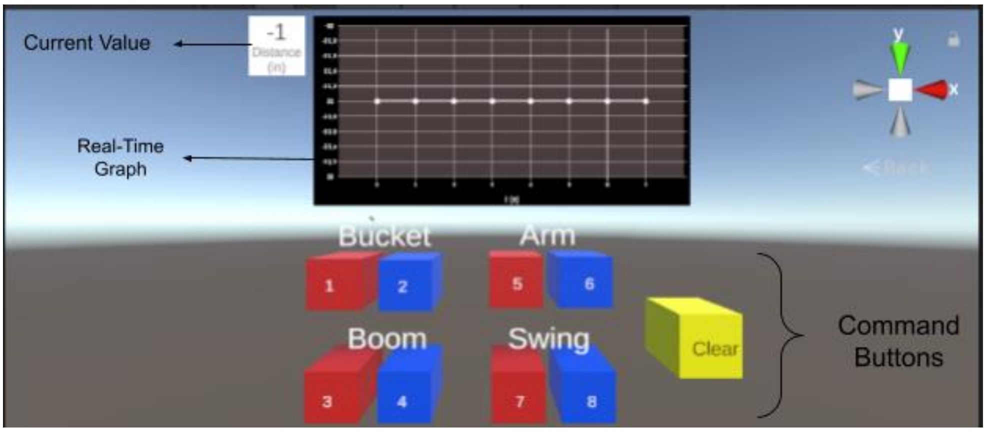

Figure 4 Unity interface with buttons and graph features.

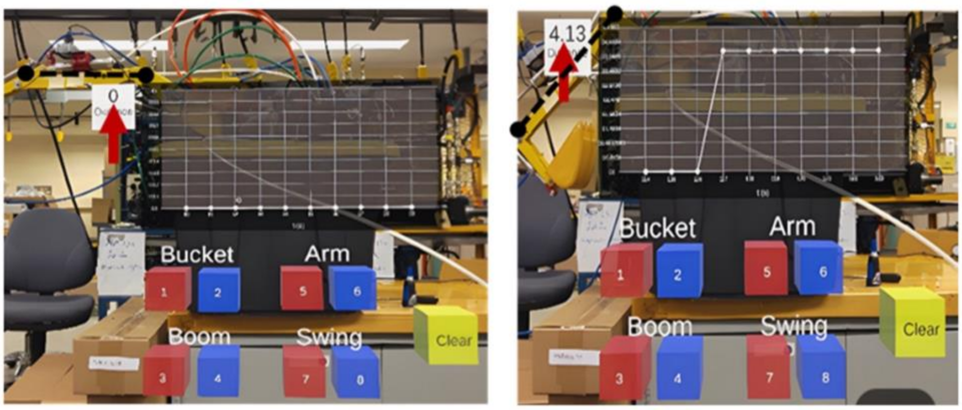

Figure 5 Retracted and extended position of the arm

Additionally, the application counts with a real-time graph that displays detailed relevant metrics of the arm. This attribute allows the users to keep track of the arm stroke in real-time, as seen on Figure 5. The instrumentation and control of the arm used on the microcontroller will be addressed in the subsequent sections.

3.2. Sensor Calibration

The potentiometer attached to the excavator's arm was used to determine the stroke of the pneumatic arm. A calibration process was conducted to convert the potentiometer's voltage into a displacement function that depends on the potentiometer output. The resulting position signal from the potentiometer is transmitted by the Wi-Fi module and presented as a virtual object in the MR environment on the HMD.

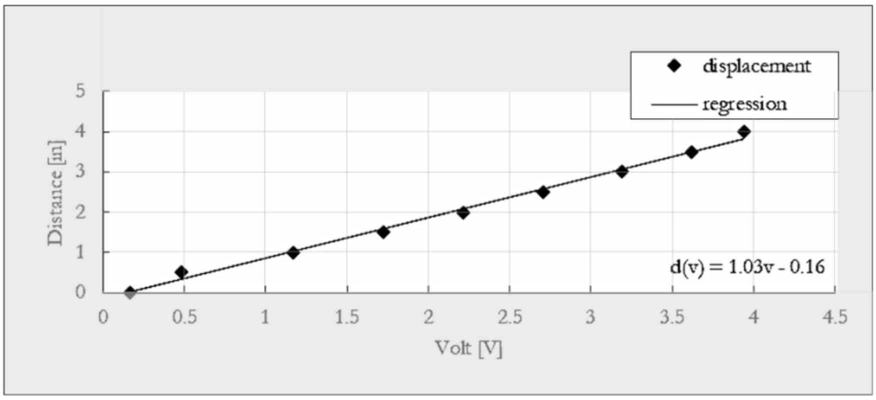

Figure 6 Calibration curve.

Figure 6 shows the calibration curve, the equation that correlates the voltage and the strokes is an input function coded on the microcontroller that, in return, sends the converted metric to HoloLens 2. The information can be displayed in real-time exactly as shown in Figures 4 and 5.

3.3. Modelling of Proportional Control

Given that the proportional control of the model excavator is not achievable using the available 5/3 pneumatic valves installed in the system, a pseudo digital approach is proposed to achieve accurate position control, Figures 6 and 7.

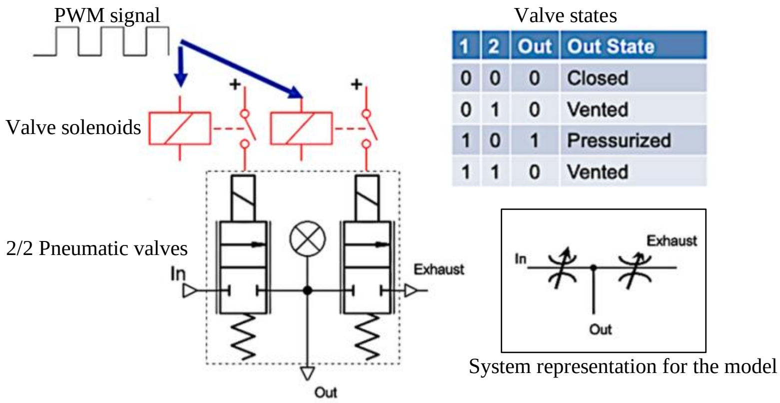

Figure 7 Electronic Pressure Regulator configuration.

This digital control is proposed to be implemented in a future iteration of the excavator model and consists of the installation of four electronic pressure regulators and single acting spring returned actuators, this, will have the objective of achieving precise position control by using PWM-like control (Figure 7). Initially, the system pressure is allowed into the inlet valve 1. The intermediate port connecting the inlet and exhaust valves is monitored by a pressure transducer, additionally a secondary control loop is added to monitor the position of the actuator (Figure 9) and simulated using Matlab Simulink.

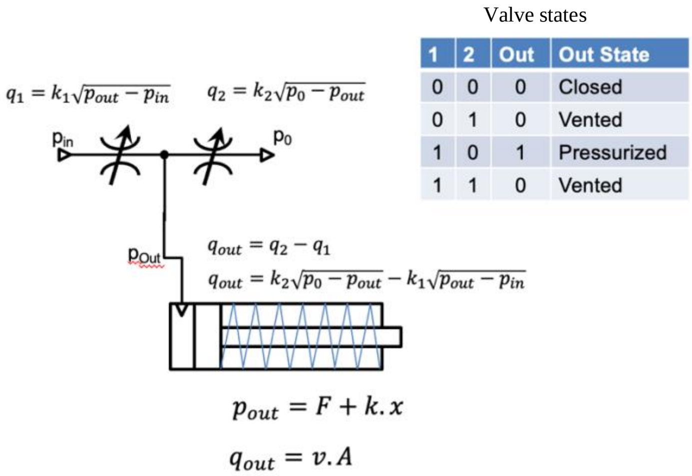

Figure 8 Pneumatic Position control using PWM regulation.

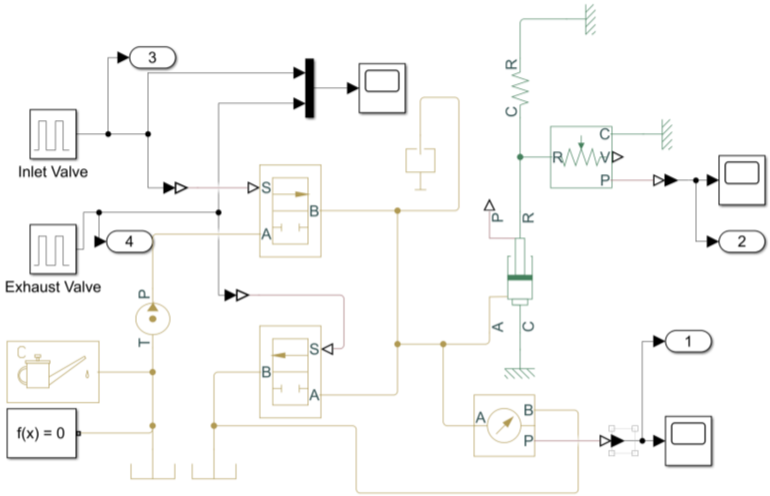

Figure 9 Simulink preliminary model of PWM position control.

Figure 10 shows the resulting simulation for the operation of the pressure regulator valves for achieving digital control of the system. This preliminary environment neglects the effects of compressibility of the pneumatic system. It is expected that this system will be implemented in the Unity environment to produce true remotely operated control of the position from a MR environment, including the compressibility effect with a first order system as shown in Equation 3.1.

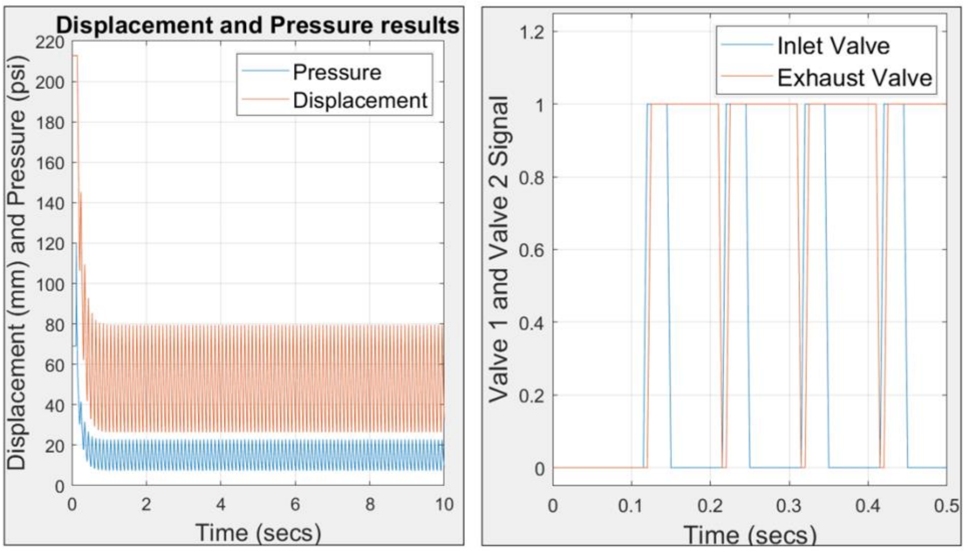

Figure 10 Preliminary position control.

$$\frac{dp_{out}}{dt} = \frac{K_1}{C}\sqrt{p_{in} - p_{out}} - \frac{K_{2.}}{C}\sqrt{p_{out}} \qquad (3.1)$$

In this proposed physical model, an accumulator is used to simulate the effects of the system compressibility. An experimental validation model has been built to simulate and validate the model as shown in Figure 11. The resulting validated model will be input into the existing MR environment in the Unity MRTK to account for the effects of compressibility and for achieving pseudo proportional control using digital valves.

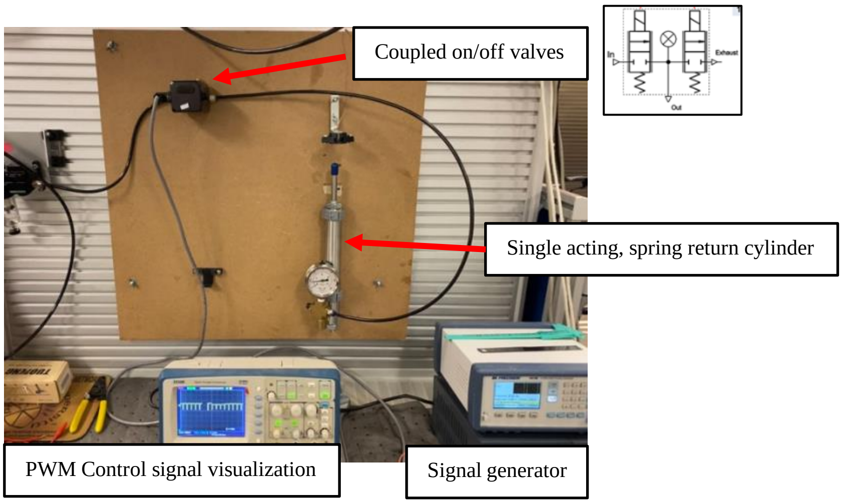

Figure 11 Experimental setup proposed to validate the compressibility effect.

4. CONCLUSIONS

Teleoperation of a pneumatic excavator was accomplished from the HoloLens 2 HMD. This is conducive to a safe operation because the user is not directly on board or in close contact with the physical scale model. Moreover, key performance indicators, namely the displacement is presented as a plot in real-time on the Mixed Reality environment.

The ability to visualize information in real-time from a safe control environment opens other paths. For example, as a future work, the XR tool can provide information of a fluid power system to evaluate its performance, or can help to take action timely in case of an impeding failure, additionally, this technology opens the door to a potential scenario where one operator may be able to control more than one machine, which would in turn increase productivity of certain lower risk operations. Another potential future work is the representation of the excavator as a digital twin. Then, the user can reproduce the different trajectories of the arm and obtain the optimal path from the digital twin. Thus, the operator can apply the optimal path of the physical object, reducing the operation's energy and time.

An approach for achieving precise position control of the actuators is explored and proposed and will be implemented as part of the future work and loaded into the Unity environment to produce a method for proportional control using Mixed Reality headsets.

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